Defense Technical Information Center Compilation Part Notice

ADP013022

TITLE: Resonant States and Terahertz Generation in Strained Semiconductors and Semiconductors Nanostructures

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [8th] Held in St. Petersburg, Russia on June 19-23, 2000 Proceedings

To order the complete compilation report, use: ADA407315

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013002 thru ADP013146

8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

FIR.02i

Resonant states and terahertz generation in strained semiconductors and semiconductors nanostructures

I. N. Yassievich†, M. S. Kagan‡ and K. A. Chao§
† Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ Institute for Radioengineering and Electronics RAS, 103907 Moscow, Russia
§ Department of Theoretical Physics, Lund University, S-223 62, Lund, Sweden

1. Introduction

Semiconductors lasers are very attractive for applications as sources of coherent radiation in the terathertz (THz) spectral region which has become an area of intensive research. The first pulsed semiconductor lasers with wavelengths in the range 100–300 μm were developed in the mid-1980s using emission from p-Ge under the simultaneous action of strong electric and magnetic fields at liquid-helium temperatures (see, for example, [1] and works cited there). A cascade laser based on intraband transitions in narrow quantum wells has been recently developed and can, in principal, operate at wavelengths from the mid-IR rang to 100 μm [2].

The stimulated emission of p-Ge subjected to uniaxial compression was observed in electric fields [3]. By analyzing the emission spectrum, it was concluded that the stimulated emission is associated with the appearance of a resonant acceptor state as a result of strain-induced splitting of the fourfold degenerate acceptor ground state [4]. This system is of unquestionable interest for developing a new type of unipolar resonant states lasers for THz range. Recently, continuous-wave operation of a such laser with possibility of broad band tuning in the range 2.5–10 THz has been demonstrated [5]. The splitting of acceptor states can be realized also in heterostructures due to internal strain and/or size quantization. In this case the splitting and the position of resonant states can be controlled by the QW width, alloy composition and/or the external transfer electric field applied. The first observation of stimulated emission from strained SiGe QW structures doped by boron has been recently observed.

Here we present a short review of theoretical investigation of resonant states induced by shallow acceptors in uniaxially strained semiconductors, mechanism of population inversion induced by external electric field, experimental results, and consideration of possible nanostructure for THz resonant states lasers.

2. Resonant states induced by shallow acceptors in uniaxially strained semiconductors

For cubic-lattice semiconductors like Ge and Si, the top of the valence band occurs in the Γ point and it is fourfold degenerate. The corresponding wavefunctions u_m are transformed according to the Γ_8^+ representation of double point group $O_r mh$. Here $m = \pm 3/2$ and $\pm 1/2$ are the z component of the total angular momentum of the hole at the Γ point. An uniaxial stress lowers the symmetry of the crystal. A stress parallel to the [001] direction changes the point group symmetry from cubic O_h to tetragonal $D_{4\mathrm{h}}$. The Γ_8^+-representation is split into two irreducible representations: Γ_6^+ for the Bloch functions $u_{\pm 3/2}$ and Γ_7^+ for the Bloch functions $u_{\pm 1/2}$. Consequently, the valence band splits into a heavy-hole (hh) and a light-hole (lh) subband with tops located below and above the initial position respectively. The

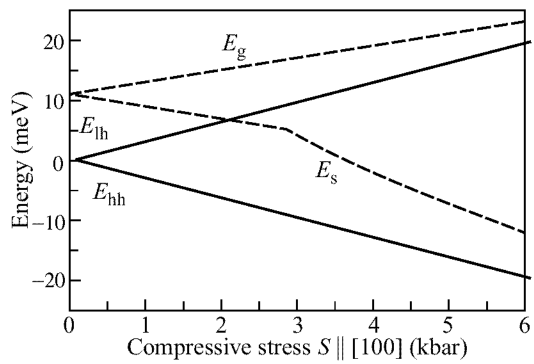

Fig. 1. The calculated energy position of the split valence-band top (solid line) and ground acceptor states (dashed line) as a function of stress applied along the [001] axis in strained Ge:Ga.

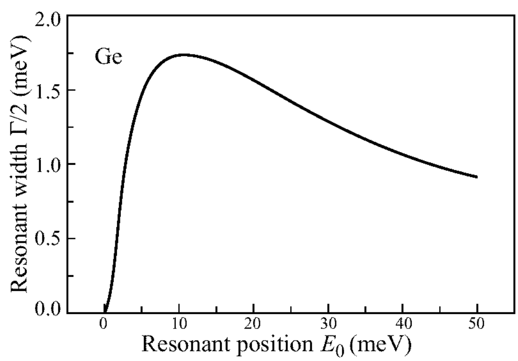

Fig. 2. The calculated resonant-level width as a function of resonant E_s-level position in p-Ge (energy E_0 being counted from the top of E_{lh}-subband).

energy difference between the valence-band tops $E_{def} = \alpha S$ where for Ge $\alpha = 6$ meV/kbar. If a stress is parallel to the [001] crystallographic direction, $\alpha = 4$ meV/kbar.

Since a shallow acceptor is attached to the valence band edge, in uniaxially strained semiconductor, both its fourfold degenerate ground state and excited states are separated into two doubly degenerate levels. Under a sufficiently strong stress $S \geq S_0$ that the valence band splitting is larger than the acceptor binding energy, two separated series of localized and resonant acceptor levels are formed. Each acceptor level attached to the heavy-hole subband overlaps with the light-hole subband $E_{lh}(\vec{k})$ and forms a resonant state via its hybridization with the extended Bloch states. The theoretical consideration of these resonant states has been done in papers [4, 6]. The calculated energy positions of the split valence band tops (E_{lh} and E_{hh}) of strained Ge and the split ground acceptor levels (E_g and E_s) of Ga are presented in Fig. 1 as a function of stress applied along the [001] axis. In this case, the threshold stress $S_0 = 2.2$ kbar. A resonant state can be characterized by a complex energy $E_0 - i\Gamma/2$ with imaginary part Γ that determines life-time h/Γ of a hole in resonant state. In Fig. 2, the calculated resonant width $\Gamma/2$ is presented as function of E_0 for Ga in Ge (here E_0 is measured from the top of the $E_{lh}(\vec{k})$ subband).

3. Lasing in strained p-Ge

3.1. Proposed mechanism of population inversion

The intracenter population inversion is formed in enough strong electric fields, when practically all holes occur in the extended states of the light-hole subband and localized acceptor states are empty due to the impact ionization. The free holes are accelerated by the external electric field applied. The scattering of the hot holes at the resonant state $M = \pm 3/2$ results in trapping of holes with energy close to the energy E_0 for a time interval of h/Γ. A theory of transport phenomena in the present of resonant states and the calculation of their population as function of the external electric field and stress have been produced by Odnoblyudov *et al.* [6, 7].

3.2. Experimental results

The Thz emission from Ga-doped Ge crystals at liquid-He temperature was measured; Ga concentration varied from 3×10^{13} to 10^{14} cm^{-3}. Crystals of size $1 \times 1 \times 10$ mm^3 were cut in [001] or [111] crystallographic direction; uniaxial stress and electric field were applied parallel to the long axis of the samples. The optical resonator was formed by the parallel lateral faces of the crystal. Thz emission was registered with a cooled Ga-doped Ge photodetector, with a grating monochromator. As was shown in [4], the spectrum of emitted radiation consists of four peaks which were identified as the hole transitions between the resonant level E_s split-off from the ground acceptor state and the local states in the energy gap. The analysis based on calculations of energy levels positions and strain dependence of the frequency related the main emission peak to the transition from the resonant E_s state to the first excited local tate of p-type symmetry. The frequency increased with stress applied (see Fig. 3).

It was found [5] that for a crystal with optical resonator planes parallel within 0.5–4 arc/min one can only observe Thz emission in pulsed regime. The minimum electric field necessary to obtain emission is 2.5 kV/cm in this case. To reach cw lasing a high-quality optical resonator was necessary. For stress applied along the [001] axis and for the resonator planes parallel within 20 arcsec or better, cw THz lasing was observed at which the main peak was corresponds to the frequency of about 2.5 THz. Fig. 4 shows the bias voltage dependence of the current and THz emission intensity at frequency of 2.5 THz. The cw regime was realized at a bias voltage below 10 V. The minimum values of the bias voltage

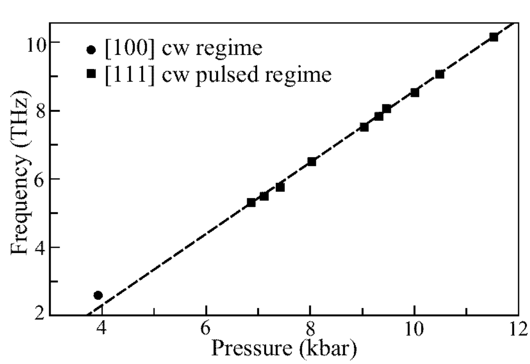

Fig. 3. Stress dependence of the frequency of the main emission peak for stress applied along the [111] (■) and [001] directions [5].

and current necessary for lasing were 2 V and 5 mA, respectively. The maximum emitted power estimated was about 1 mW in pulse regime and at least of 1–2μW in the cw regime.

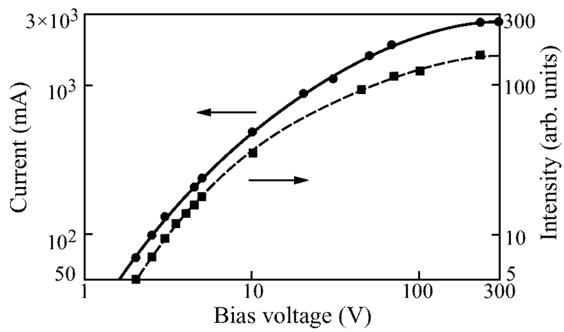

Fig. 4. The bias voltage dependence of the current and THz emission intensity for stress along the [001] axis. The cw regime was realized at bias voltage below 10 V [5].

The concept of emission with participation of resonant states is supported by several additional facts. The minimum pressure at which stimulated emission could be observed corresponds exactly to the threshold pressure S_0 at which the split-off acceptor level E_s arrives into the continuous spectrum for both [001] and [111] directions. On the other hand, the intensity of the stimulated emission decreases sharply at pressure along the [001] axis of 8 kbar. Depopulation of the resonant state begins at this pressure due to possible emission of optical phonon.

4. Nanostructures suitable for THz lasing

Doped SiGe/Si and InGaAs/AlGaAs QW structures are considered as promising systems to realize inversion phenomena due to shallow acceptor states which are split-off by size quantization and strain without any external stress. The intense Thz emission of stimulated character has been observed in Si/SiGe/Si QW structures doped with boron. It has been demonstrated that stimulated intra-center emission is possible in a strain single-QW inclined by a transverse potential. The special paper of Altukhov et al will be presented on this problem. The 2D structures provide the unique possibility to employ A^+-centers which can exist in thermal equilibrium here in contrast to the bulk where they can appear only due to external excitation. We present also some ideas about the possibility to use QW-surface states and states induced by acceptors in barriers.

Acknowledgments

We gratefully acknowledge the support by Russian Foundation for Basic Research (Grants 98-02-18268, 99-02-116169) and by Russian Ministry of Science and Technology (Grant 97-10-55).

References

[1] A. A. Andronov, *Sov. Phys. Semicond.* **21**, 701 (1987);
in *Spectroscopy of Nonequilibrium Electrons and Phonons*, ed C. V. Shank and B. P. Zakharchenya, *Modern Problems in Condensed Matter Sciences* Vol 35 (North-Holland, Amsterdam, 1992).

[2] J. Faist, F. Capasso, D. L. Silco et al., *Science* **264**, 553 (1994).

[3] I. A. Altukhov, M. S. Kagan, K. A. Korolev, V. P. Sinis and F. A. Smirnov, *Sov. Phys. JETF* **74,** 404 (1992);
I. A. Altukhov, M. S. Kagan, K. A. Korolev and V. P. Sinis, *Sov. Phys. JETF Lett.* **59**, 476 (1994).

[4] I. A. Altukhov, K. A. Korolev, V. P. Sinis, E. G. Ghirkova, M. A. Odnoblyudov and I. N. Yassievich, *JETF* **88,** 51 (1999).

[5] Yu. P. Gousev, I. A. Altukhov, M. S. Kagan, K. A. Korolev, V. P. Sinis, M. S. Kagan, E. E. Haller, M. A. Odnoblyudov, I. N. Yassievich and K. A. Chao, *Appl. Phys. Lett.* **75**, 757 (1999).

[6] M. A. Odnoblyudov, I. N. Yassievich, V. M. Chistyakov and K.-A. Chao, presented to *Phys. Rev. B.*

[7] M. A. Odnoblyudov, I. N. Yassievich, M. S. Kagan, Yu. M. Galperin and K.-A. Chao, *Phys. Rev. Lett.* **83**, 644 (1999).

[8] A. Taguchi, K. Takahei, M. Matsuoka and S. Tohno, *J. Appl. Phys.* **84**, 4471 (1998).

[9] J. M. Langer, T. Langer, G. L. Pearson, B. Krukowska-Fulde and U. Piekara, *Phys. Stat. Solidi (b)* **66**, 537 (1974).

[10] M. S. Bresler, O. B. Gusev, B. P. Zakharchenya and I. N. Yassievich, *Phys. Solid State* **38**, 813 (1996) [translated from Fiz. Tverd. Tela **38**, 1474 (1996)].